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6. AUTHOR(S)
H. J. Kuno

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
QuinStar Technology, Inc.
1725 Del Amo Blvd.
Torrance, CA 90501

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
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2800 Powder Mill Road
Adelphi, MD 20783-1197

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Final Technical Report

MicroElectro Mechanical Millimeter-Wave Control Devices for Affordable Scanning Antennas

SBIR Phase I

Contract # DAAL01-96-C-0041

Prepared For

Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783-1197

By

QuinStar Technology, Inc.

November 1996

1725 Del Amo Boulevard, Torrance, California 90501, Phone (310) 320-1111/Fax (310) 320-9968

Final Technical Report
MicroElectro Mechanical Millimeter-Wave Control Devices
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SBIR Phase I
Contract #DAAL01-96-C-0041
Period Covering May 15 - November 14, 1996

Abstract
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The objective of the Phase I effort of this project was to investigate and demonstrate the feasibility of the novel MicroElectroMechanical (MEM) control device technology for millimeter-wave systems, such as phased array radars and wideband communication systems. During Phase I, MEM SPST and SPDT switches, and single bit phase shifters have been designed, developed, fabricated, and tested. The MEM control devices have successfully been operated at millimeter-wave frequencies. The MEM switches have demonstrated SPST and SPDT switching with insertion loss less than 1.5 dB, isolation greater than 20 dB, and switching time less than 18 μs at Ka-band. The analytical model developed in Phase I projects the MEM control device operation through and beyond 100 GHz. The Phase I effort has demonstrated, both experimentally and theoretically, the feasibility of the MEM control devices as enabling technology for developing affordable millimeter-wave systems.

SBIR Phase I Final Technical Report
MicroEletroMechanical (MEM) Millimeter-Wave Control Devices
for Affordable Scanning Antennas (Topic No. A95-031)

Introduction

Millimeter-wave systems offer many unique features that the short wave length provides such as small antenna size, wide band width, high resolution, together with penetration capability through fog, clouds, dust and smoke. To develop affordable millimeter-wave systems, low cost control devices capable of low insertion loss at high frequencies are needed. The proposed MEM millimeter-wave control devices offer

- Low cost, enabling technology for affordable millimeter-wave systems
- High frequency operation, high figure of merit, low insertion loss.
- High power switching and phase shifting
- Semiconductor process and MMIC compatibility

The objective of the proposed project is to develop novel MEM device technology that will enable the development of affordable millimeter-wave systems.

This report describes the results of the Phase I effort of the project covering the period from May 15 through November 14, 1996. In section A, the results of the Phase I work is summarized. Detailed design considerations and optimization approaches for the MEM switches are discussed in Section B. This project was carried out by the team consisting of QuinStar Technology as prime contractor and David Sarnoff Research Center as subcontractor.

A. Results of the Phase I Work

The objective of the Phase I effort was to investigate and demonstrate the feasibility of the novel MicroElectroMechanical (MEM) control device technology for affordable millimeter-wave systems. We have designed, developed, fabricated, and tested MEM SPST and SPDT switches, and successfully operated them at millimeter frequencies. We believe that this is the first test result of MEM control devices operated in the millimeter-wave range. The Phase I effort has demonstrated, both experimentally and theoretically, the feasibility of the proposed MEM control devices as enabling technology for developing affordable millimeter-wave systems such as scanning antennas, phased array radars, and wide band communication systems.

A.1 Objectives of Phase I Effort

The objective of the Phase I effort was to demonstrate the feasibility of developing low cost MicroEelectroMechanical (MEM) control devices for millimeter-wave applications such as scanning array antennas and wide band communications. Specifically the Phase I effort to date was directed to the design, development, fabrication, and testing of MEM switches that will serve as building blocks for various millimeter-wave control devices such as T/R switches, phase shifters, and multiplexers. During the remaining period of the Phase I, we will fabricate and test single bit MEM phase shifters that consist of a pair of STDT switches and delay lines.

A.2 Research Conducted

We have conducted the following research tasks to date:

- Detailed design and analysis of MEM switches in SPST and SPDT configurations that are the basic building blocks for phase shifters, T/R /switches, and multiplexers.
- Fabrication of MEM switches; mask layout and fabrication of SPST and SPDT switches in both microstrip and coplanar forms.
- Theoretical understanding of MEM switch structure design requirements for millimeter-wave operations; MEM switch frequency response, switching voltage, and switching speed.
- Establishment of basic MEM fabrication process steps.
- Design and construction of test circuits and fixtures.
- Test and evaluation of MEM switches.
- Design of single bit phase shifter.
- Fabrication and evaluation of phase shifters.
- Test and evaluation of phase shifters
- Successful demonstration of the feasibility of MEM devices for millimeter-wave systems.

A.3 Findings and Results

During the Phase I of this project, we have successfully demonstrated the feasibility of MEM control devices for millimeter-wave applications. The following analytical and experimental results have been achieved:

- MEM SPST and SPDT switches design. Detailed designs of MEM switch structures have been made and analyzed. The analysis has shown that cut off frequencies greater than 1,000 GHz and operating frequencies up to and beyond 100 GHz can be achieved. Shown in Fig. A-1 is the basic design of the switches developed. We designed SPST and SPDT switches both in microstripline and coplanar configurations. The basic switch consists of a micro vane on a post, 50 ohm input and output transmission line sections, and control voltage line. The 50 ohm transmission line sections which occupy a large part of the die are for input and output connections. Since the active portion of the MEM switch that is located at the center is very small, the MEM switches can be made much smaller than the current size of 0.040" x 0.040". This chip size was chosen for easier handling during testing.
- Fabrication of MEM switches. A set of process masks have been designed and made. The MEM switches have successfully been fabricated. Shown in Fig. A-2 are the microphotographs of SPST and SPDT switches. The switches were diced to 0.040" x 0.040" size chips. The scanning electron microscope photographs as shown in Fig. A-3 show details of the vane of the MEM switches fabricated.
- Special RF test fixtures. Millimeter-wave test fixtures as shown in Fig. A-4a have been designed and fabricated. The first set of test fixtures are designed for frequencies from 2 to 40 GHz with K-connectors. The second set, which are with V-connectors operates in the 40 - 60 GHz range. The third set, which are of waveguide circuit configuration, are for 90 - 100 GHz testing.

- Millimeter-wave tests. The MEM switches have been mounted on to the test fixture as shown in Fig. A-4b and have been tested and evaluated. The switches have successfully operated from 2 to 40 GHz. The measured data on one of the SPST switches is shown in Fig. A-5a. The switch performed over the entire band except the resonance detected in the 20 - 30 GHz range. We believe this is due to RF coupling to the bias line, which should be correctable by adding low pass filter to the line. Testing was successfully extended to the 40 - 60 GHz range although we encountered more unwanted mismatch resonances in this range. Shown in Fig. A-5b are the closed insertion loss and open isolation data measured on a SPST MEM switch at frequencies where input and output matchings were good. This data illustrates the feasibility of operationg the MEM swtches through the 60 GHz range.The SPDT switch data measured over 12.5 - 40 GHz is shown in Fig. A-6. The SPDT operated up to the upper limit of the measured band, i.e., 40 GHz. We also detected the resonance response at 20-26 and 32 -34 GHz. Low pass filters will be added to the control lines in the future design.
- Theoretical modeling. We gained theoretical understanding and modeling of MEM switching, i.e., device parameters, structure, frequency response, switching voltage, and switching speed, with which we can develop design rules and optimization techniques. The results of this task are included in Section B.
- Switching voltage. We measured voltage required to activate the MEM switches ranging from 20 v to 28 v. Although these values are slightly higher than the calculated value of 16.6 v, the data validated the MEM switch model to the first order. We detected a difference between turn on and turn off voltages, i.e., turn on at 25 V and turn off at 20 V, for example. We need to investigate the cause and effects of this phenomenon in Phase II.
- Switching speed. We have tested the MEM switches for their switching speed using the set up as shown in Fig. B-10. Turn on time (i.e., from open to close) of 12 μs and turn off time of 18 μs were measured. This is in reasonable agreement with the calculated value of 4.6 μs. Although this switching time is slower than PIN diode switches, it is sufficiently fast for scanning antennas and other applications with improved RF performance.
- MEM device fabrication process steps. Basic fabrication process steps for the MEM devices have been developed. Detailed process instructions for each step have been documented.
- Phase shifters. Single bit switched line phase shifters were designed. The phase shifter consists of a pair of SPDT switches and transmission lines as shown in Fig. A-7.

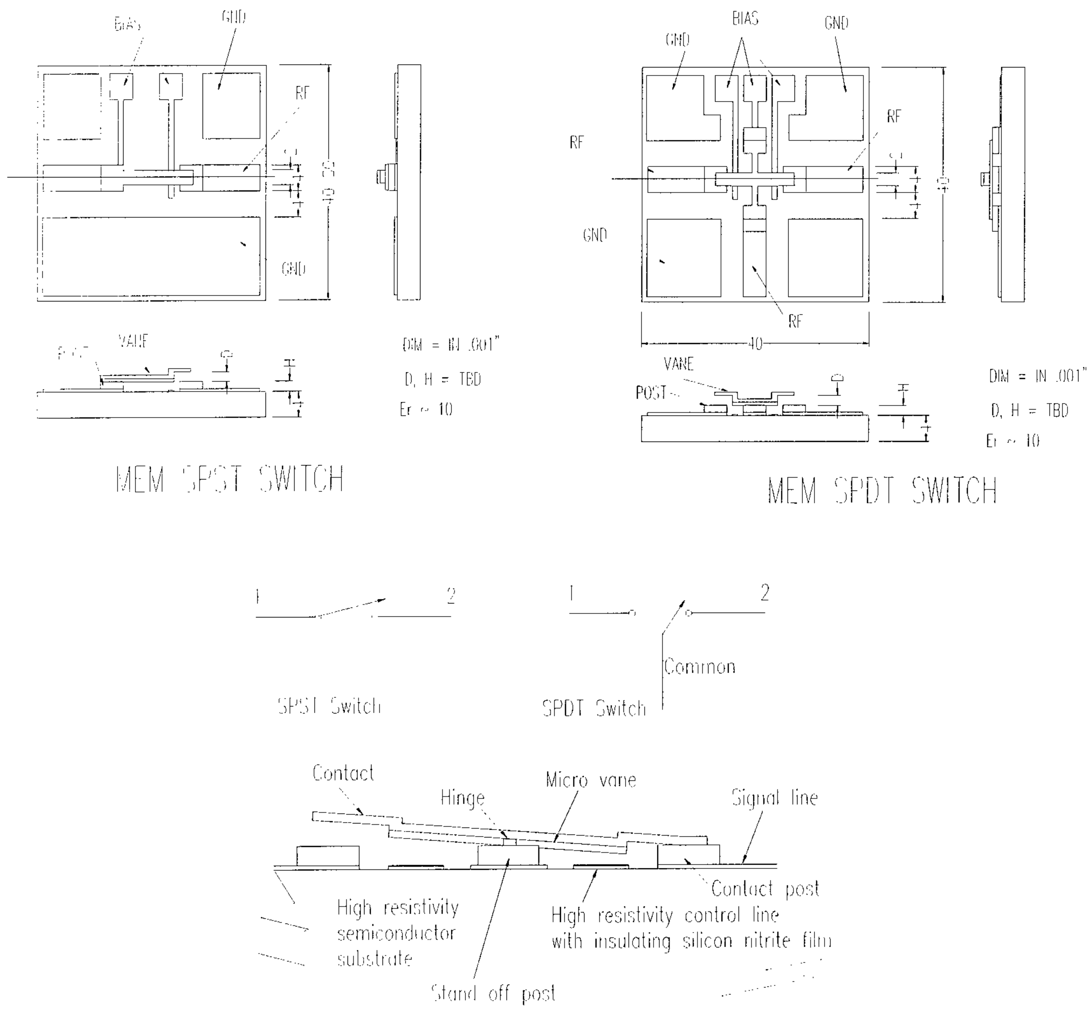
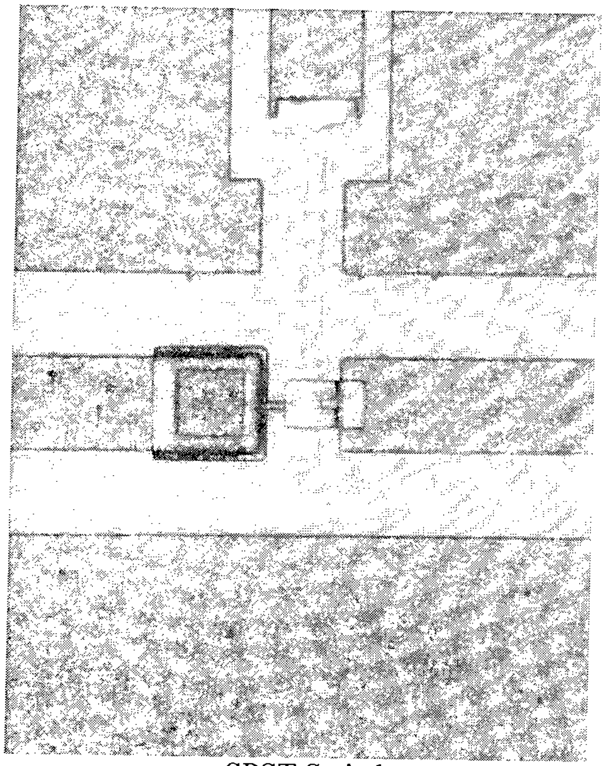
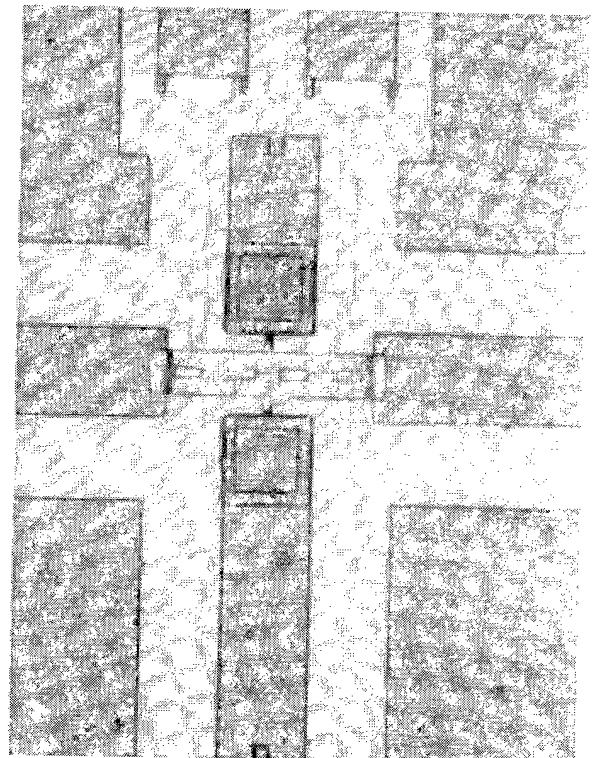


Figure A-1 MicroElectroMechanical millimeter-wave switches--- Basic SPST and SPDT switch designs with 50 ohm transmission line input and output.

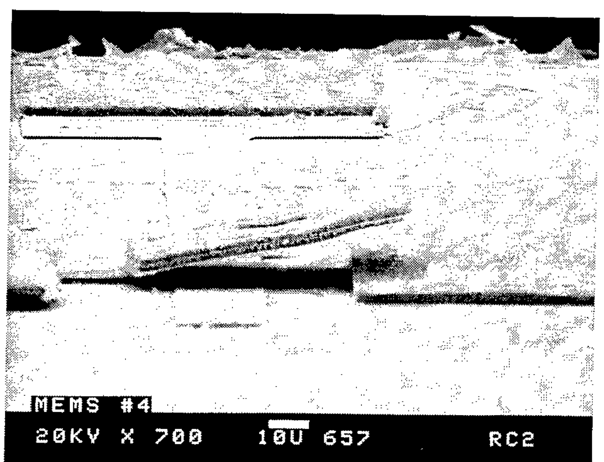


SPST Switch

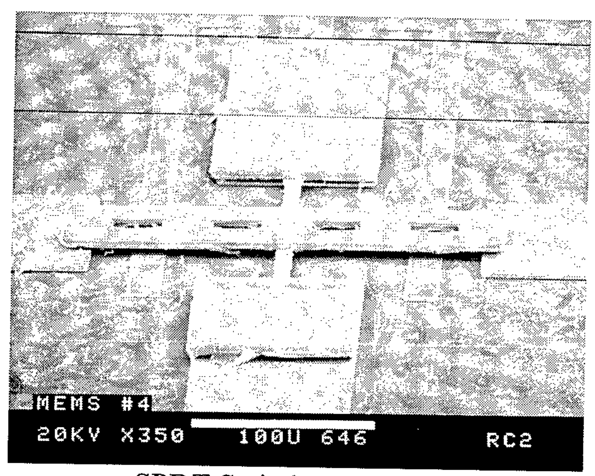


SPDT Switch

Figure A-2 Micro photographs MicroElectroMechanical SPST and SPDT switches fabricated in Phase I. The switches have successfully been operated at millimeter-wave frequencies.



SPST Switch



SPDT Switch

Figure A-3 Scanning electron microscope photographes showing details of MicroElectroMechanical SPST and SPDTswitches fabricated in Phase I.

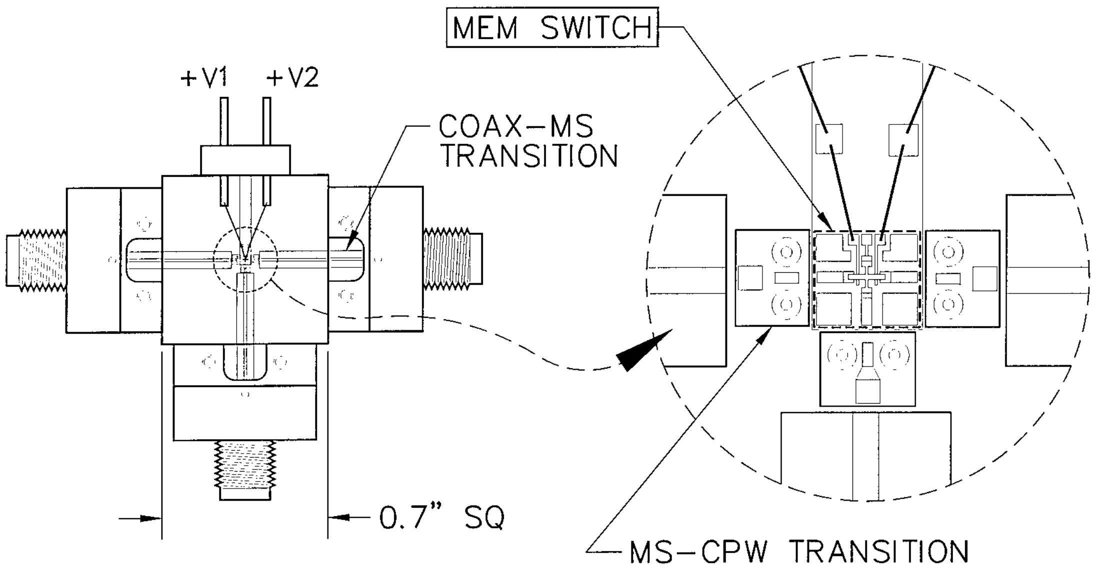


Figure A-4a. Test fixture designed for microelectromechanical switches of 0.040" x 0.040" size. With K-connectors at input and output, it operates up to 40 GHz. With V-connectors it operates up to 60 GHz. For testing at 94 GHz, the input and output ports will be WR-10 waveguides with microstrip proves.

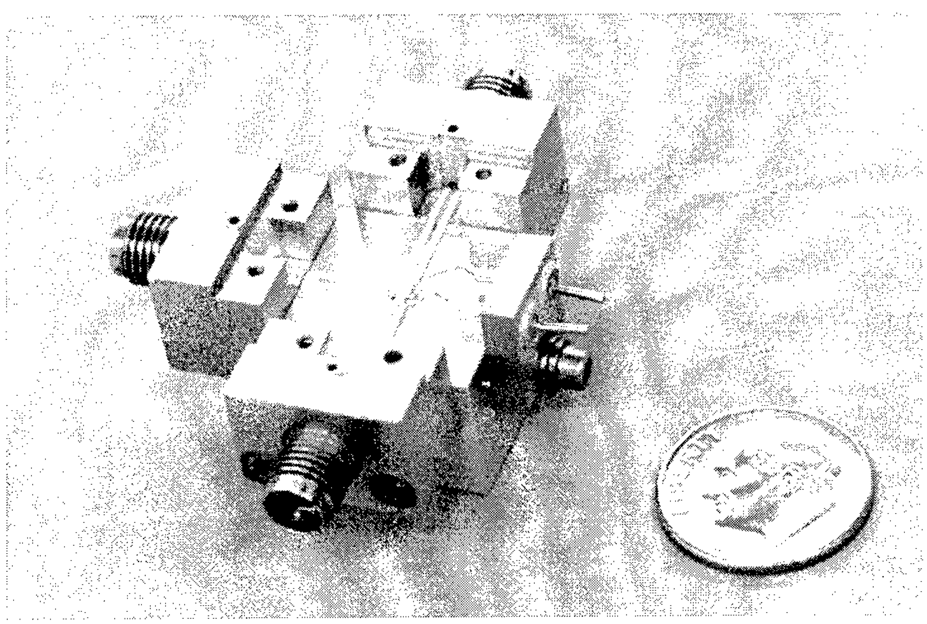


Figure A-4b Photograph of the MEM test fixture with a MEM SPDT chip mounted. It was successfully operated up to 60 GHz in Phase I.

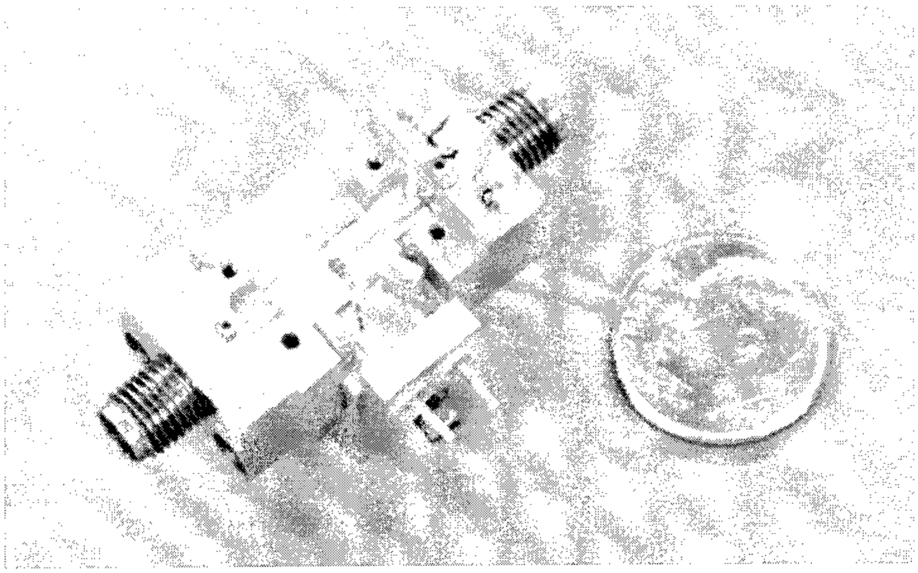


Figure A-4c Photograph of the MEM test fixture with a MEM SPST chip mounted. It was successfully operated up to 60 GHz in Phase I.

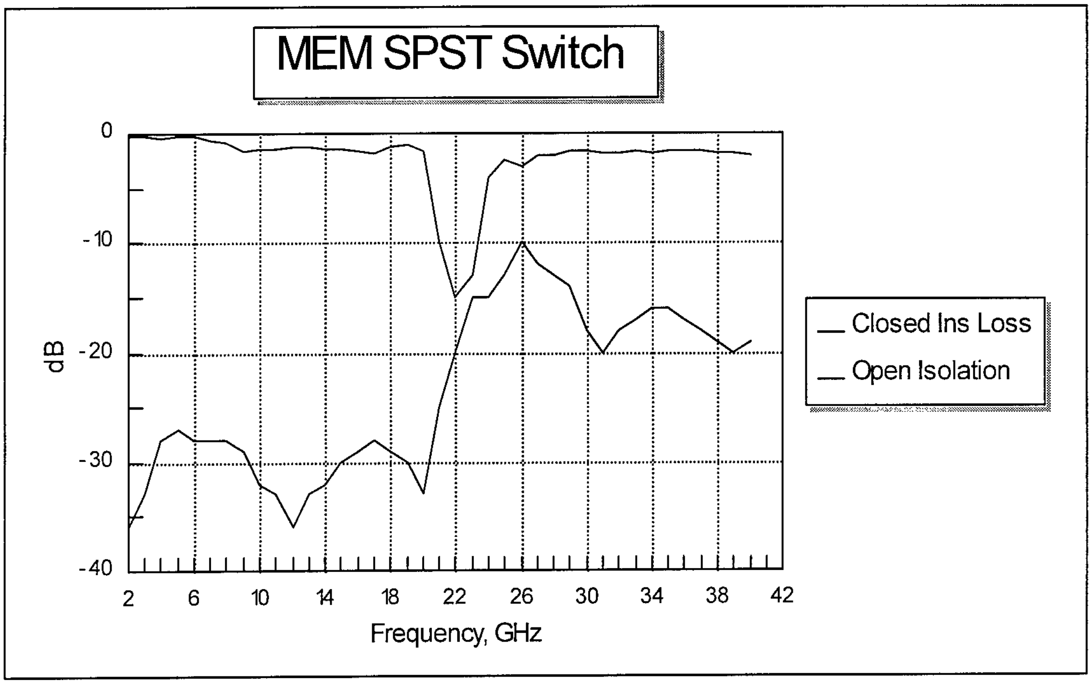


Figure A-5a Measured frequency response of MEM SPST switch developed in Phase I. The switch operated from 2 to 40 GHz. Unwanted resonance in the 20 - 30 GHz range suggests that improved control voltage line design with a low pass filter will be needed to eliminate RF coupling to the control line.

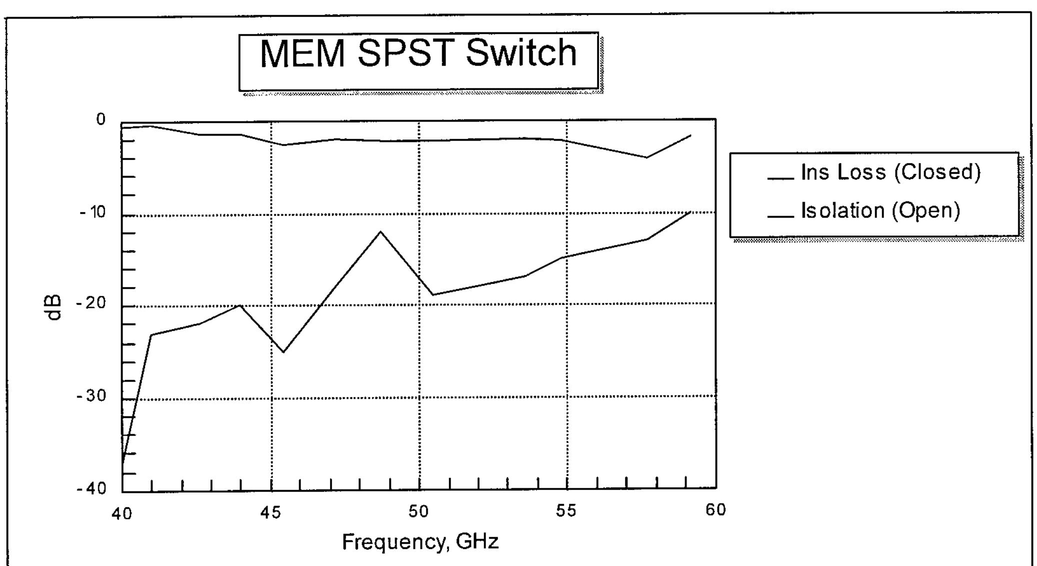


Figure A-5b Frequency response of MEM SPST switch developed in Phase I. The switch operation was successfully extended into the 40-60 GHz range. The closed insertion loss and open isolation were mesured at frequencies where input and output matchings are good.

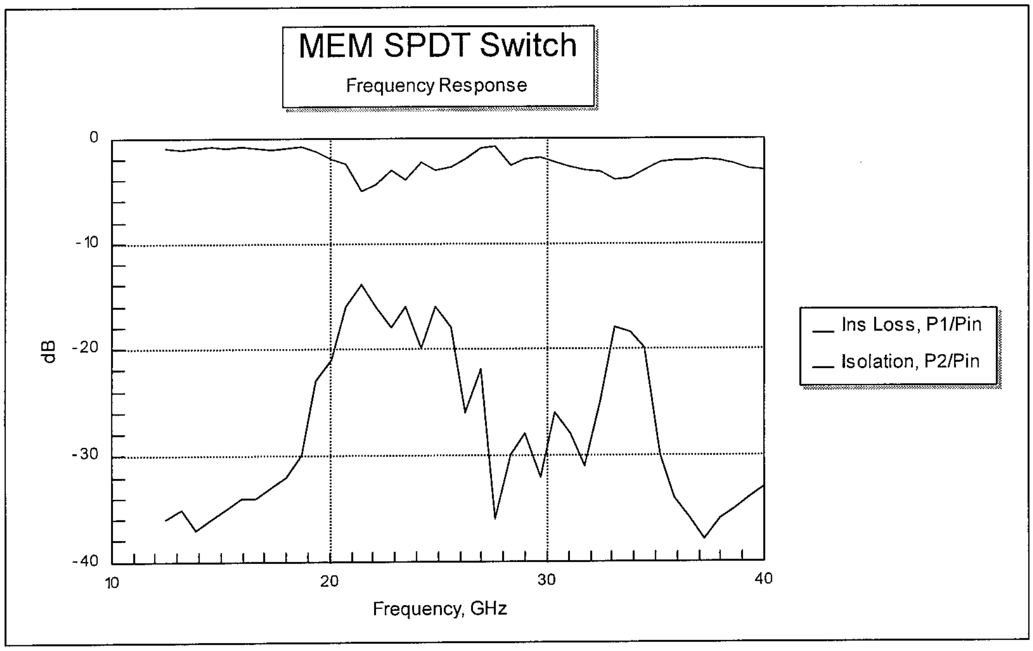


Figure A-6 Measured frequency response of SPDT MEM switch developed in Phase I. Resonance in the 19 -26 and 32 - 34 GHz range should be solvable with low pass filters added to control lines.

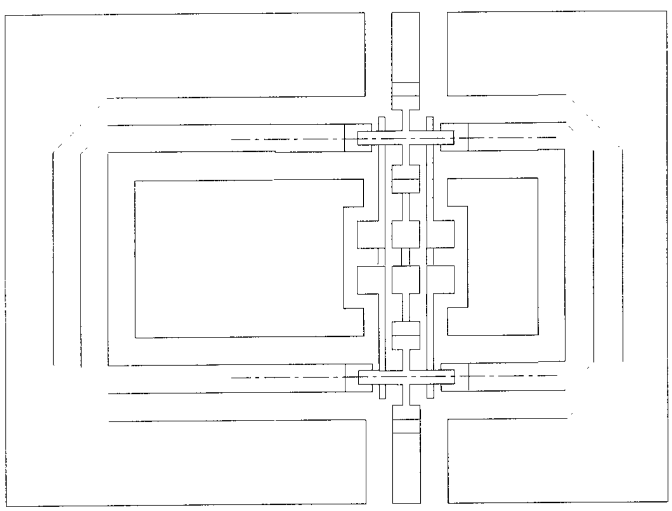


Figure A-7 MEM Switched line 34 GHz phase shifter consisting of two SPDT switches, transmission lines, and control lines. The circuit is 0.070" x 0.100" in size.

A.4 Fabrication Process

The MEM process developed in the Phase I of the program represents a blend of process techniques originally developed for passive MIC circuits on ceramic substrates and MMICs on GaAs substrates. For the Phase I feasibility demonstration device fabrication, we chose alumina and sapphire substrates. For the metal, we decided to use the metal systems we are familiar with rather than directing extensive optimization effort in the limited time available in Phase I. We fabricated MEM switches with titanium - gold system, which is compatible with GaAs MMIC processing. A survey of MEM literature indicates aluminum is generally the metal of choice because it is compatible with silicon process. The basic fabrication process steps used in Phase I are depicted in Fig. A-8. Although we have developed the basic MEM device fabrication process and successfully fabricated MEM switches that demonstrated the millimeter-wave operation, we did not direct significant amount of effort toward optimizing the fabrication steps in Phase I.

A.5 Technical Feasibility

Based on the experimental results achieved with the MEM switches fabricated and tested as part of the Phase I effort to date, the feasibility of low cost, high performance MEM control devices for affordable millimeter-wave scanning antennas and wireless communication systems has clearly been demonstrated. This conclusion is also backed by the theoretical understanding of the switching mechanism and frequency response analyses and simulations carried out in Phase I. The MEM switches have been fabricated, successfully operated at millimeter-wave, and identified problems to solve. The MEM device fabrication process is not only compatible with but also simpler than semiconductor device or MMIC processing since there are no active devices in MEM. Therefore the MEM technology offers high potential for achieving low production costs and integration into MMICs.

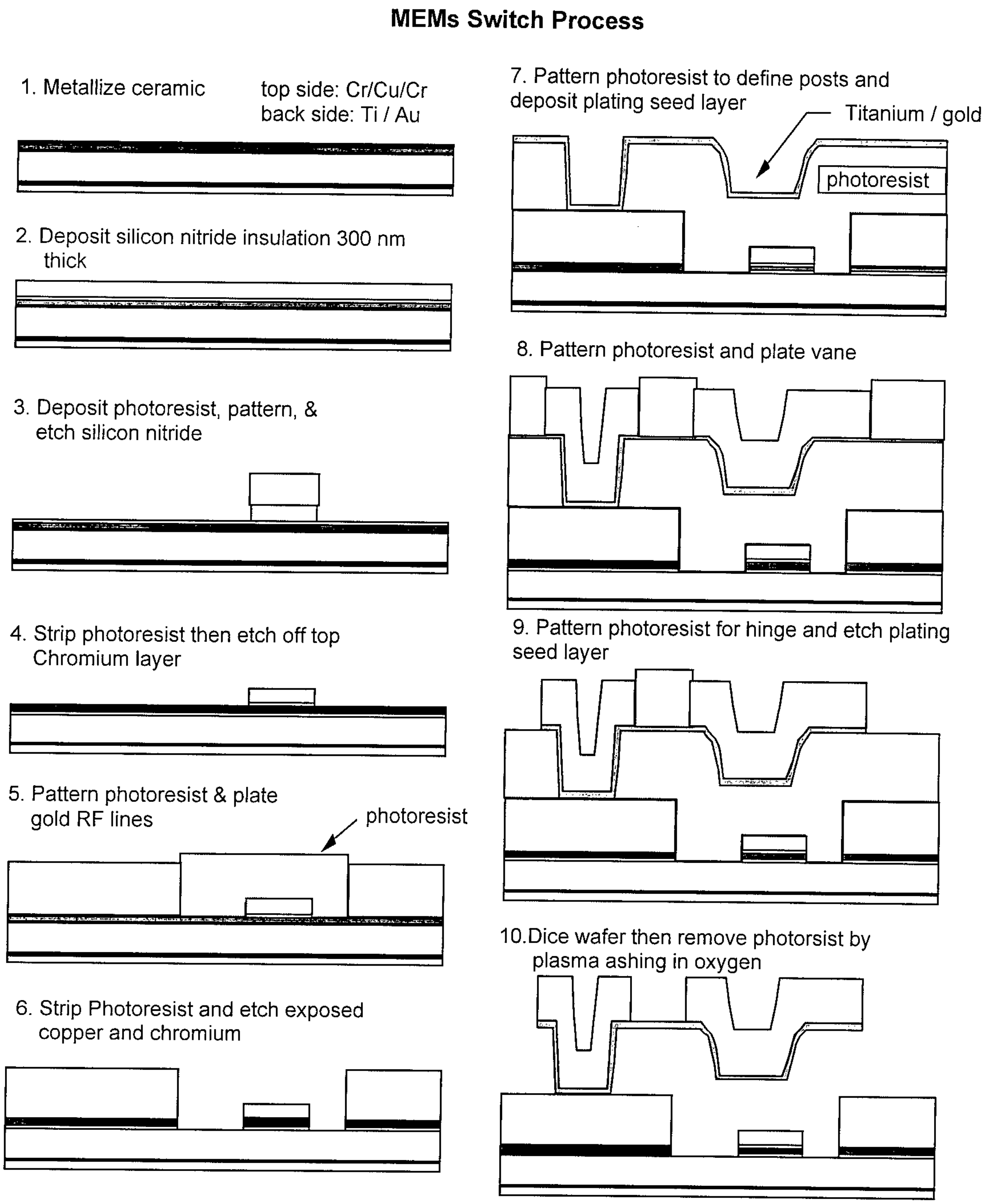


Figure A-8 Basic MEM device fabrication process developed. Using this process millimeter-wave MEM switches have successfully been fabricated in Phase I.

B. MEM Switch Design Considerations

MEM switch design considerations and optimization methodology based on the physical models have been developed during the Phase I. In this section, the switch structures, switch configurations, RF characteristics, switching voltage requirement, and switching speed considerations are discused in detail.

B.1 MEM Switch Structures

The basic switch structure we have developed for the MEM switches during Phase I consists of a switching micro vane, transmission line sections, and bias voltage line as shown in Fig. B-1. In Phase I, it was shown that the MEM switch operates at millimeter-waves. In Phase I, the frequency response problem caused by coupling between the RF and control lines was also identified, which will be addressed in Phase II as discussed later in this section. RF characteristics of the MEM switch can be represented by an equivalent circuit as shown in Fig. B-2. When the switch is closed, it is simply a small series contact resistance Rs and inductance Ls. Since the vane dimensions are small, the effect of the inductance may be neglected in most applications. When it is open, the switch is represented by a capacitance Cs. For the geometry of the MEM switches developed in Phase I, Cs is calculated to be 0.015 pf. The measured contact resistance is in the 1 to 5 ohm range. Thus the MEM switches have a very high figure of merit (cut off frequency = $1/2\pi RC$) of 2,000 - 10,000 GHz.

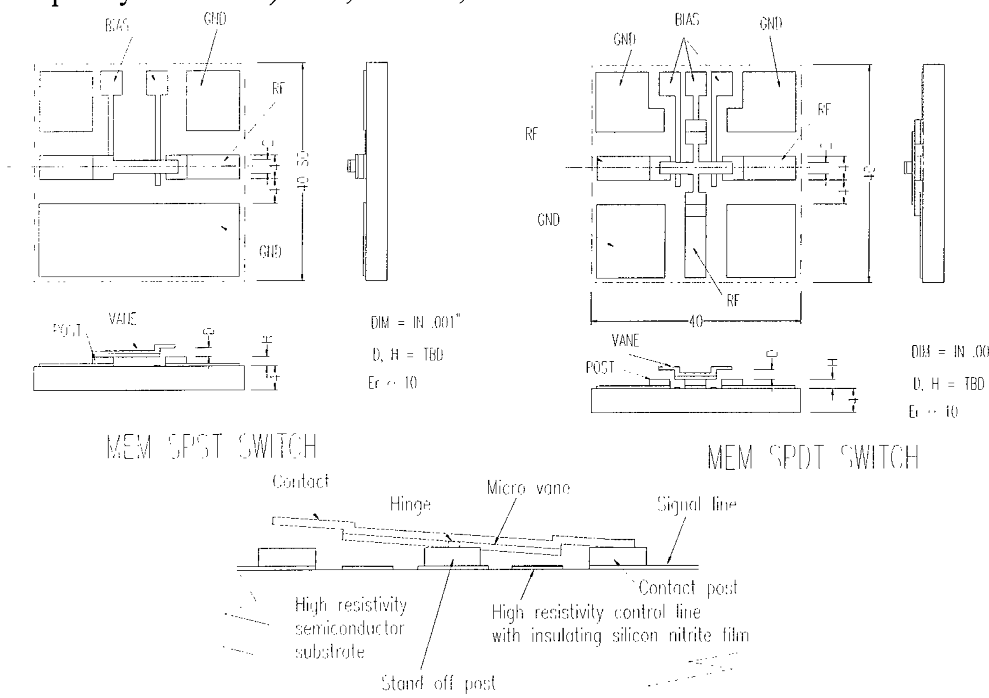


Figure B-1 Basic MEM switch structure (SPDT is illustrated in the front view). The switch consists of a micro vane, 50 ohm transmission line input/output, and control voltage line. The switching vane dimensions are very small (0.003" x 0.004" approx.). Thus MEM switches can be made very small. Fabrication steps follow standard MMIC and semiconductor metalization process on high resistivity semiconductor or dielectric surface without semiconductor devices.

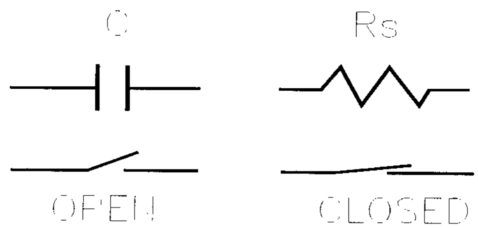


Figure B-2 MEM switch may be represented by simple equivalent circuits; small capacitance C when open, and small resistance R when closed. With C = 0.015pf and R = 1 ~ 5 ohm, the MEM switches have $f_c = 1/2\pi RC$ = 2,000 ~ 10,000 GHz

The basic parameters to be considered in the switch design optimization are

- Configuration
- Frequency response: Insertion loss/Isolation/Return loss vs. frequency
- Switching voltage
- Switching speed
- Control voltage line
- Size

B2. Switch Configurations

Switch configurations to be considered are series, shunt, SPST, and SPDT configurations as shown in Fig. B-3. The basic transmission line used in the switches are microstrip and coplanar circuits. These circuits offer small size, compatibility to most MMICs, and design simplicity, and operate well through 40 GHz and beyond. At frequencies above 60 GHz, however, the microstrip and coplanar circuits as transmission lines show increased losses and higher order mode problems. For this reason, waveguide and finline (E-plane) circuits are commonly used at high millimeter-wave frequencies..

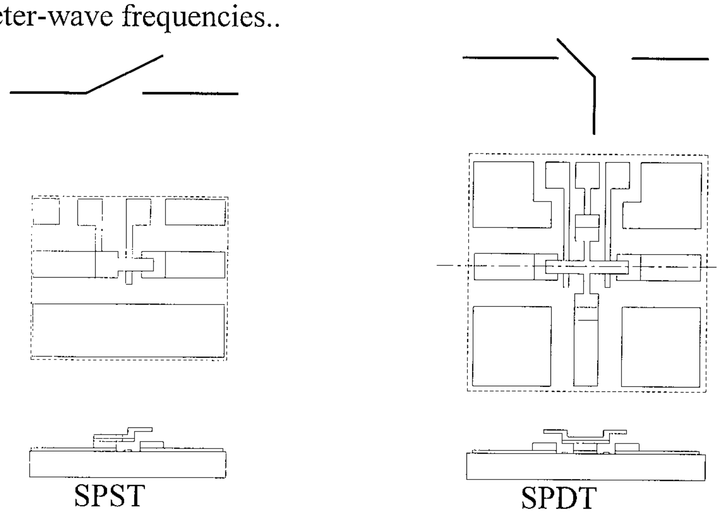


Figure B-3 MEM SPST and SPDT switch configurations.

B3. Frequency Responses

Frequency response is mainly determined by the value of the open position capacitance, transmission line characteristic impedance, and contact series resistance. In Phase I, the MEM switches have successfully been operated at millimeter-wave frequencies. The problem of coupling between RF and control lines affecting the frequency response was also identified, which will be addressed later in this section. For the basic series SPST switch as shown in Fig B-4a, the insertion loss and isolation can be calculated from transmission line equations. We get

$IL = -5 \text{ Log } [(1 + (Rs/Zo))^2 + (\omega L/Zo)^2]$ for series switch closed

$Iso = -10 \text{ Log } [(1 + (1/2\omega CZo)^2]$ for series switch open

where $\omega = 2\pi f$, f = frequency, Zo = 50 ohm = characteristic impedance of transmission line. Since Rs << Zo, and $\omega L/Zo << 1$, insertion loss due to the switch is very small. The isolation of open switch calculated as a function of frequency is shown in Fig. B-4b. It can be seen that, in order to achieve isolation greater than 20 dB, we need $\omega CZo < 0.05$. At 100 GHz, for example, we need C < 0.016 pf. The decrease in isolation of the switch in open position with increasing frequency is a main limiting factor for millimeter-wave operation. It is important to minimize the capacitance between the vane and the transmission line. The capacitance value between a pair of parallel plates may be calculated from

$C = \varepsilon_o A/d$

where $\varepsilon_o = 8.85$ pf/m is free space capacitivity (permittivity), A is the effective area, and d is the separation distance. For the MEM switch we designed, we have d = 3 μm, A = 100 μm x 50 μm, and we get C = 0.015 pf. Thus, we should be able to operate such a switch up to the 100 GHz range.

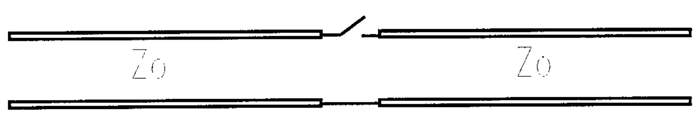


Figure B-4a MEM millimeter-wave SPST switch connected in series

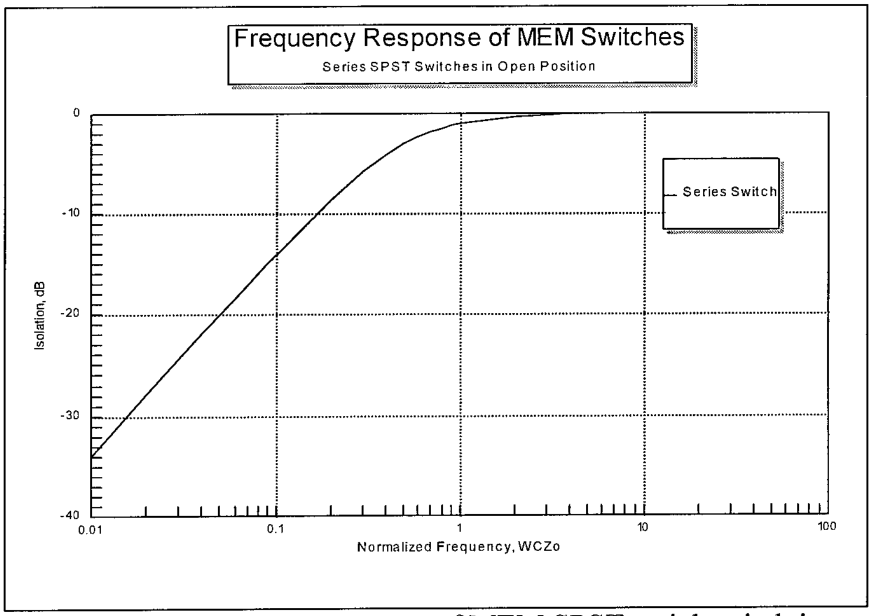


Figure B-4b Frequency response of MEM SPST serial switch in open position--- Isolation vs. Normalized frequency, ωCZo. Decrease in isolation at high frequency is due to the open switch acting like a capacitor connected in series the 50 ohm line. Insertion loss of the closed switch with Rs < 5 ohm is less than 0.1 dB.

Similarly, for a shunt SPST switch as shown in Fig. B-5a, we have

$$IL = -10 \text{ Log}[1 + (\omega CZo/2)^2] \quad \text{for shunt switch open.}$$

Since the shunt path as a finite length, it must be taken into consideration in calculating isolation of the shunt switch in closed position. From transmission line equations, we get

$$Iso = -10 \text{ Log}[1 + (Zo/2Zs)^2 \text{ Cot}^2 \theta] \quad \text{for shunt switch closed}$$

where Zs = equivalent characteristic impedance of the shunt path, $\theta = \omega\ell$ = effective electrical length of the shunt path. Insertion loss and isolation of shunt SPST MEM switch calculated as a function of frequency are shown in Figs. B-5b and B-5c.

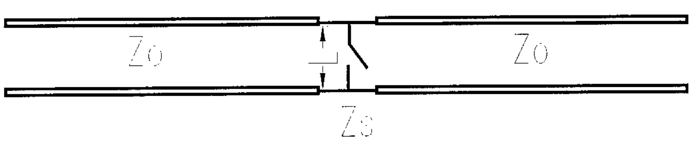


Figure B-5a MEM switch in shunt position. Finite length of shunt path has noticeable effect on frequency response of the switch.

In order to get insertion loss of less than 0.5 dB, we need $\omega CZo < 0.5$, which is relatively easy to achieve. To achieve isolation greater than 20 dB with shunt SPST switch, we need $\theta < 3$ degrees if Zo/Zs = 1. This is not difficult to achieve at low frequencies. However, at 100 GHz for example, 2 degrees in electrical length is only 25 μm in physical length, which is somewhat difficult to realize. However, if we choose Zo/Zs = 2, then the length of the shunt path can be increased to 50 μm, which becomes easier to fabricate.

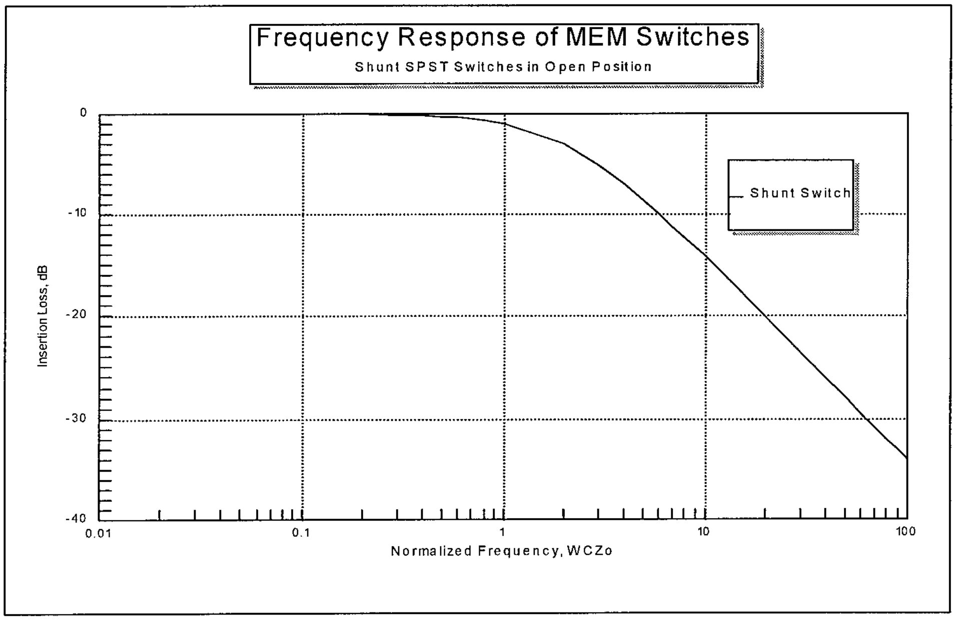


Figure B-5b Frequency response of MEM SPST shunt switch in open position--- Insertion loss vs. normalized frequency, ωCZo. Insertion loss is due to the open shunt switch acting like a shunt capacitor.

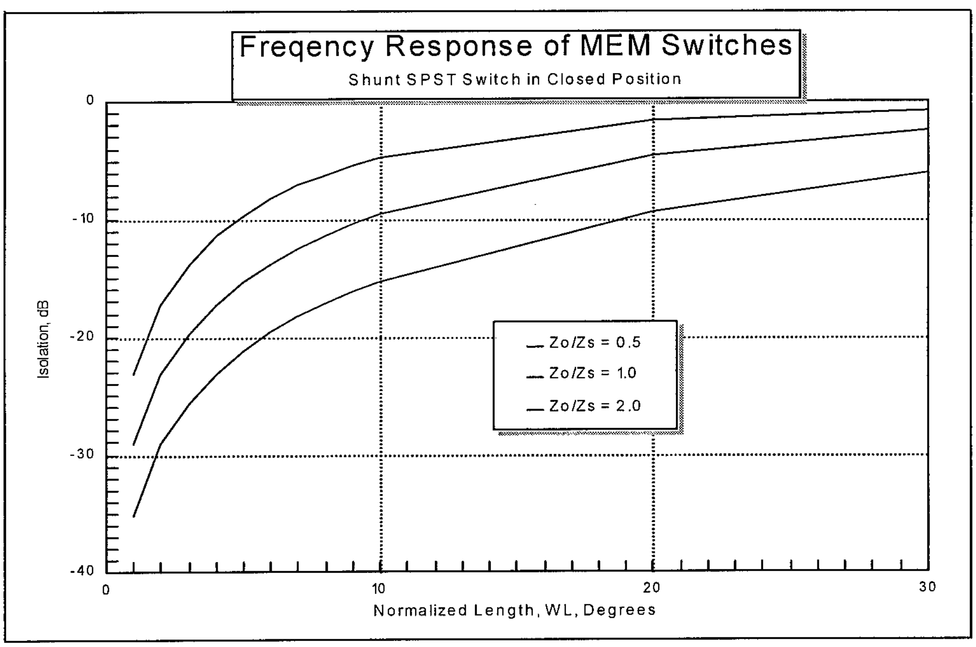


Figure B-5c Frequency response of MEM SPST shunt switch in closed position--- Isolation vs. normalized frequency, ωCZo. Isolation is due to reflection of RF power by the closed shunt switch behaving like an inductor.

Thus we can construct SPST MEM switches for operation up to 100 GHz either in series or shunt configuration. The series configuration is better suited for microstrip line circuits and the shunt configuration is for coplanar waveguide (CPW) circuits.

For the SPDT switch as shown in Fig. B-6a, we can similarly analyze its performance, i.e., frequency response.

Return loss at the common (input) port is given by

$$RL = Pr/Pi = - \mathrm{Log}\,[9 + (2/\omega CZo)^2\,]$$

Insertion loss from the common port to output port 1 with closed switch, and isolation from the common port to output port 2 with open switch are respectively given by

$$IL = P1/Pi = 10\,\mathrm{Log}\,[\{8 + (2/\omega CZo)^2\}/\{9 + (2/\omega CZo)^2\}] - 5\,\mathrm{Log}\,[\{4 + (1/\omega CZo)^2\}/\{1 + (1/\omega CZo)^2\}]$$

$$Iso = P2/Pi = 10\,\mathrm{Log}\,[\{8 + (2/\omega CZo)^2\}/\{9 + (2/\omega CZo)^2\}] - 5\,\mathrm{Log}\,[4 + (1/\omega CZo)^2]$$

Shown in Fig. B-6b are return loss, insertion loss, and isolation of MEM SPDT switches calculated as a function of frequency. It is not easy to obtain conditions $\omega CZo < 0.01$ at frequencies near 100 GHz. Thus we expect that isolation decreases to about 16 dB at 100 GHz.

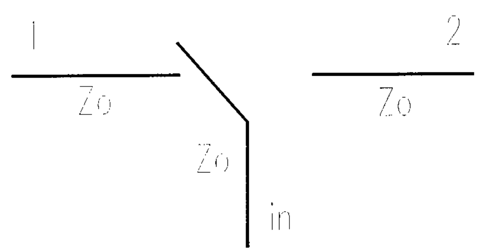


Figure B-6a SPDT switch configuration

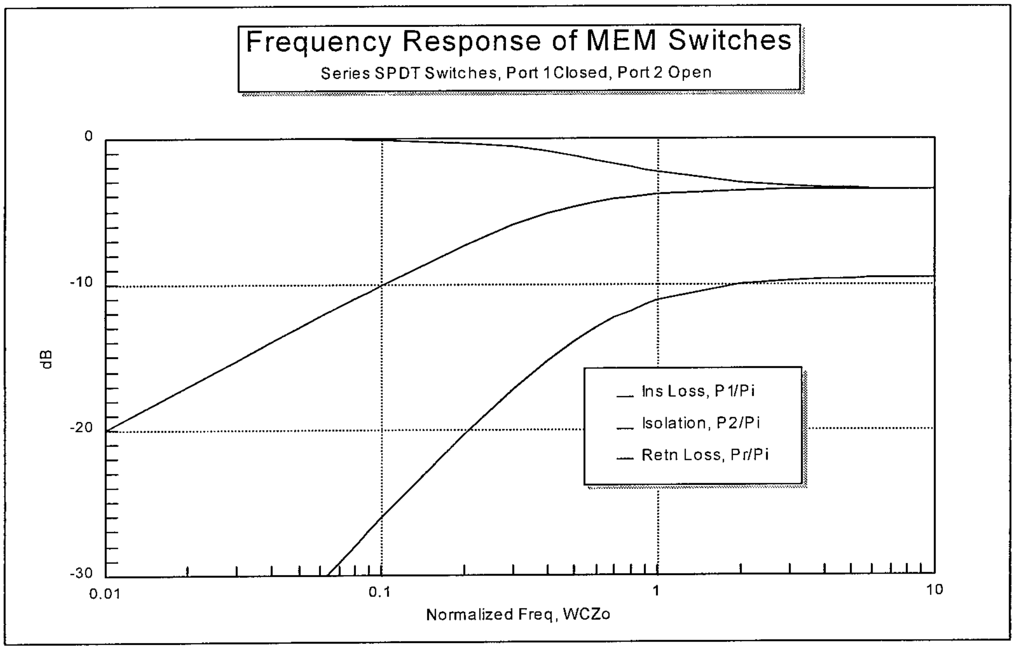


Figure B-6b Frequency response of MEM SPDT switches calculated as a function of normalized frequency, ωCZo.

For applications where high isolation is desired, we can combine series and shunt configurations in a SPDT switch as shown in Fig. B-7. Since the shunt element would not affect insertion loss significantly, this configuration is attractive when high isolation is desired.

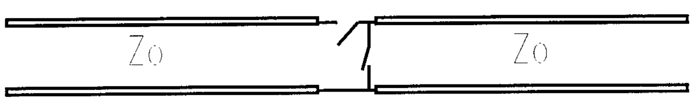


Figure B-7 Combination of series and shunt configurations increases isolation in a MEM switch without affecting insertion loss.

B.4 Switching Voltage

The switching action is initiated by the Coulomb force to bend the micro vane as illustrated in Fig. B-8. The Coulomb force is equal to

$$F = QE = \varepsilon_o V^2 A/h^2 = \varepsilon_o V^2 wa/h^2$$

where h is the height of the vane position from the bias line, A = wa is the effective area created by the micro vane width (w) and bias line width (a), and V is the applied voltage.

The amount of deflection (g - h) of the vane of thickness b, width w, and length ℓ caused by the Coulomb force F is given by

$$g - h = F\ell^3/3EI = F\ell^3/3E\,(wb^3/12) = 4F\ell^3/E\,(wb^3)$$

where E = modulus of elasticity of the vane and I is the moment of inertia of the vane cross section.

From the two equations above, we get

$$F = (g - h)(Ewb^3/4\ell^3) = \varepsilon_o V^2 wa/h^2$$

$$h^2(g - h) = K V^2 , \quad \text{where } K = 4\varepsilon_o a\,\ell^3/Eb^3$$

Note that this equation has 3 solutions for h values (2 positive and 1 negative) if V is relatively small and that it has one negative solution if V is relatively large as illustrated in Fig. B-9. In other words, if V < Vc where Vc is the critical value, the switch will be partially deflected but not closed, and, if V > Vc, then the switch will be closed.

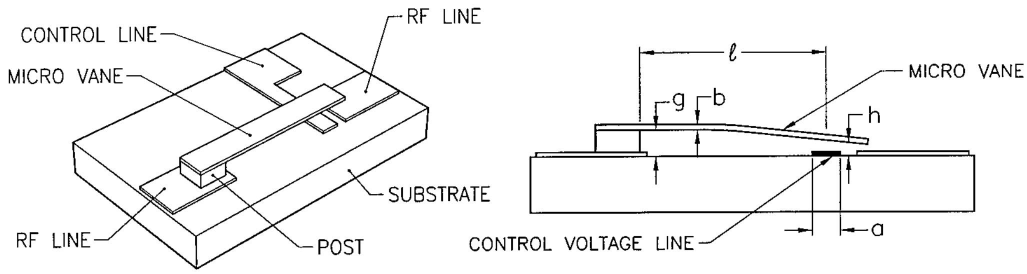


Figure B-8 MEM model for determining switching voltage

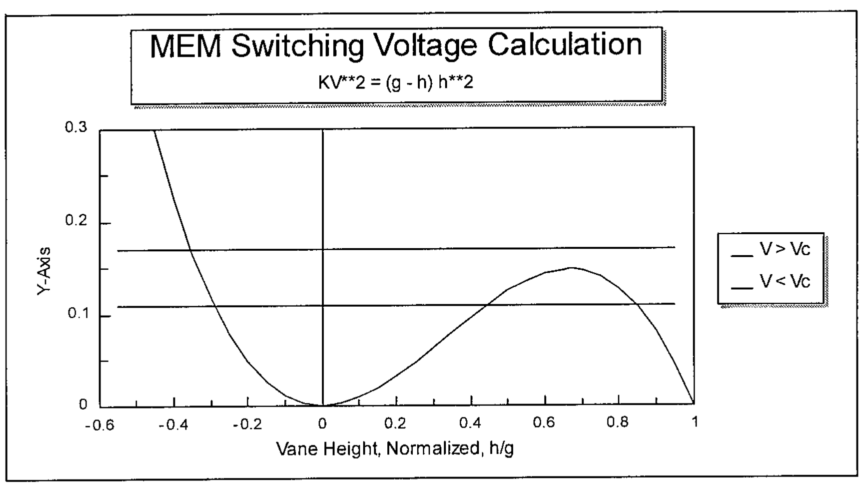


Figure B-9 MEM switching voltage determination

$h^2(g - h) = K V^2$, $K = 4\varepsilon_o a\,\ell^3/Eb^3$, $Vc = [(E/\varepsilon_o a)\{gb/3\ell\}^3]^{1/2}$

To find the value of Vc, differentiating with respect to h and V, we get

$$dh/dV = 2 K V/h(2g - 3h)$$

Note that, when h = 2g/3 or 0, dh/dV becomes unstable. This is the critical point where the vane switches completely. The critical voltage value for the switch to close can be found by substituting h = 2g/3 into the above force equation.

$$KVc^2 = (4/27)g^3 \qquad \text{or}$$

$$Vc = [(E/\varepsilon_o a)\{gb/3\ell\}^3]^{1/2}$$

Note that the critical switching voltage varies with the gap as $g^{3/2}$ function. This is in agreement with the recently published result (C. Goldsmith et al, 1996 IEEE MTTs International Microwave Symposium Digest, June 1996, pp. 1141-1144). For the switch dimensions of our design, where we have g = 3 μm, b = 0.5 μm, a = 25 μm, ℓ = 62 μm, E = 17 x 10^6 pound per sq. inch for typical metals, we find that Vc = 16.6 volt. We measured Vc = 20 - 28 volt on our MEM switches. We believe that the variation and difference between the calculated and measured values are due to variations in the gap size (g) and micro vane thickness (b). By increasing the switching vane length to 100 μm, we can reduce the switching voltage to 8.1 volt. By decreasing the micro vane thickness and gap slightly, we should be able to further reduce the switching voltage to 5 volt. Note that the MEM switches requires bias voltage, but no current to switch, thus they do not dissipate any bias power.

B.5 Switching Speed

Since the mass of the micro vane is very small, we can expect fast switching time. An estimated switching time may be calculated in the following manner:

With the MEM switch model shown in Fig. B-10, torque applied to the vane is

$$T = F\ell = V^2 \varepsilon_0 wba \ell / h^2 = I \alpha$$

$$I = \rho\, wb\ell^3 / 12$$

$$t = [2g/\alpha\ell]^{1/2}$$

where α = angular acceleration, ρ = mass density of the vane, I = moment of inertia, t = switching time, and h_{max} = g. This assumes the torque remain constant. This is a reasonable assumption since, as the vane is bent down, the Coulomb force increases but the counteracting metal stress force also increases. Solving for t, we get

$$t = [\rho b \ell\, g^3 / 6\varepsilon_0 a V^2]^{1/2}$$

For b = 0.5 μm, ℓ = 100 μm, g = 3 μm, a = 25 μm, ρ = 19 gm/cm^3 , we get

$$t = 4.6 \times 10^{-5}/V \text{ sec.}$$

At V = 10 v, we get t = 4.6 μs. Thus we can expect the switching time of a few microseconds from the MEM switches. We have tested the switching time using the set up as shown in Fig. B-11. We measured turn on time of 12 μs and turn off time of 16 μs, which are in a reasonable agreement with the calculated value.

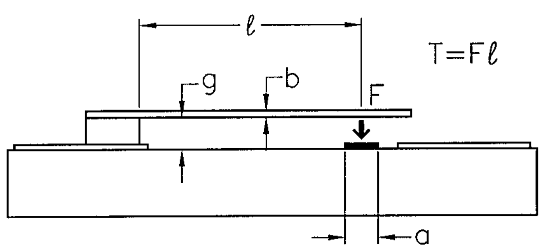


Figure B-10 MEM switch model for switching speed analysis.

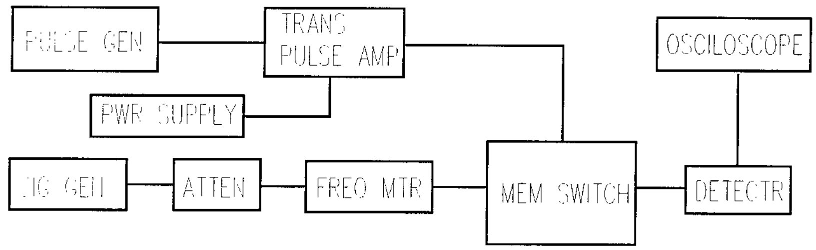


Figure B-11 Test set up for switching time measurement of MEM switches

B.6 Control Voltage Line

Since the switch control voltage line couples to the micro vane, which carries RF signal, special attention must be paid to prevent the RF signal from coupling to the bias lines. In Phase I testing, we found that RF signal can couple to bias lines at certain frequencies affecting the frequency response of the switch. To address this problem, we need to design low pass filters and incorporate them into the bias lines. Designing low pass filters is generally straight forward. However, the filters for the MEM switches must reject wide range of frequencies covering from 1 to 100 GHz (or at least from 30 to 100 GHz).

In addition to integrating low pass filters, we must make trade off between RF coupling and switching voltage in optimizing the control line design. By decreasing the effective coupling area between the RF and control lines, RF coupling will decrease but the Coulomb force will decrease thereby increasing switching voltage requirement. To compensate for the decrease in the Coulomb force, the length of the switch vane may need to be increased.